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**Strong WW Scattering Physics: A Comparative Study  
for the LHC, NLC and a Muon Collider**

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**STRONG WW SCATTERING PHYSICS:  
A COMPARATIVE STUDY FOR  
THE LHC, NLC AND A MUON COLLIDER \***

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ABSTRACT

We discuss the model independent parameterization for a strongly interacting electroweak sector. Phenomenological studies are made to probe such a sector for future colliders such as the LHC,  $e^+e^-$  Linear collider and a muon collider.

## 1. Introduction

The “Higgs puzzle” is clearly the most prominent question in the contemporary high energy physics. Despite the extraordinary success of the Standard Model (SM) in describing particle physics up to the highest energy available today, the nature of electroweak symmetry-breaking (EWSB) remains undetermined. Since any consistent EWSB theory will produce Goldstone bosons, which become the longitudinal degrees of freedom of the electroweak gauge bosons (generically denoted by  $W_L$  unless specified otherwise), scattering of the Goldstone bosons would be the most direct means to explore the nature of the EWSB. In particular, it is conceivable that there is no light ( $\lesssim 800$  GeV) Higgs boson. General arguments based on partial wave unitarity then imply that the electroweak gauge bosons develop strong (non-perturbative) interactions by energy scales of order 1–2 TeV and new physics beyond the weakly coupled Higgs sector must show up<sup>1</sup>. For a collider to probe such energy scales, the CM energy must be sufficient that gauge-boson scattering at subprocess energies at or above 1 TeV occurs with substantial frequency. The CERN Large Hadron Collider (LHC) would have the potential to reach this physics. Other colliders under discussions that potentially meet this requirement are the linear  $e^+e^-$  collider with  $\sqrt{s} \sim 1.5 - 2$  TeV (denoted by NLC) and a high energy muon collider  $\sqrt{s} \sim 4$  TeV.

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<sup>1</sup>Invited talk given at the Ringberg Workshop, *The Higgs puzzle – What can we learn from LEP II, LHC, NLC, and FMC?* Ringberg Castle, Germany, Dec. 8–13, 1996.

In this talk, we first discuss parameterizations for a Strongly-interacting Electro-Weak Sector (SEWS) in a (relatively) model-independent way. Based on this picture, we then make a comparative study at those future colliders for exploring the SEWS physics.

## 2. Strongly Interacting Electroweak Sector

Models with dynamical electroweak symmetry breaking often include strong self-interactions among the Goldstone bosons. Technicolor theories are typical examples of this kind<sup>2</sup>. Unfortunately, there are no phenomenologically successful models to describe such SEWS physics. To avoid conflict with the current precision electroweak measurements, a phenomenological approach to study this class of physics is to only concentrate on the minimal EWSB sector, and to parameterize the underlying physics in a way independent of the detail dynamics by an effective Lagrangian, governed only by certain well motivated symmetries<sup>3</sup>.

### 2.1. “Model Independent” Parameterization

Motivated by the Standard Model electroweak gauge symmetry  $SU(2)_L \times U(1)_Y$  and realizing the approximate global symmetry  $SU(2)_c$  (the custodial symmetry), one may start from a global chiral symmetry  $SU(2)_L \times SU(2)_R$ . Parameterizing the would-be Goldstone boson fields,  $w^\pm$  and  $z$  through the matrix

$$\Sigma = \exp(i\vec{\sigma} \cdot \vec{w}/v) , \quad (1)$$

we can construct an effective Lagrangian that contains this very general information:

$$\mathcal{L} = \frac{v^2}{4} \text{Tr} \partial_\mu \Sigma \partial^\mu \Sigma^\dagger . \quad (2)$$

This is the lowest order in terms of the derivative expansion and is model independent. Higher order terms can be introduced systematically<sup>3,4</sup>, but we choose to take this simplest case of Eq. (2) as a representative. The Goldstone boson scattering follows the Low energy theorem<sup>5</sup> (LET) and there are no resonances under consideration. However, the scattering amplitudes in this case violate the unitarity near 1–2 TeV region. For simplicity, we choose here to unitarize them by the K-matrix technique, with the model<sup>6</sup> named LET-K.

Going beyond the non-resonance model, one can introduce a nonlinearly-realized chiral model with a spin-zero, isospin-zero resonance ( $S$ ). The physics of this model is dominated by a new particle with the quantum numbers of the Higgs boson. For definitiveness in our presentation, we will choose the scalar mass  $M_S = 1$  TeV and width  $\Gamma_S = 350$  GeV<sup>6</sup>. Similarly, one can study a nonlinearly-realized chiral model with a spin-one, isospin-one resonance<sup>7,6</sup>. The physics in this case is dominated by a

(techni- $\rho$ -like) vector particle. We choose the mass-width combinations  $(M_V, \Gamma_V) = (1 \text{ TeV}, 5.7 \text{ GeV})$  and  $(2.5 \text{ TeV}, 520 \text{ GeV})$ . These models are fully described in Ref. 6.

## 2.2. Low-lying States: Co-existence?

The separate consideration on each individual low-lying state in a strongly-interacting sector may be incomplete. The well-known example is the strong interactions of hadrons in which the requirement of good high energy behavior of  $S$ -matrix elements gives rise to a set of Adler-Weisberger (AW) type sum rules for forward scattering amplitudes<sup>8</sup>. To satisfy these sum rules, besides the Goldstone bosons  $\pi$ 's, the other states such as  $\rho, \sigma, a_1$  and  $\omega$  are required to coexist. It thus implies a scenario for the strongly-interacting electroweak sector which contains a rich spectrum of low-lying states<sup>9</sup>, including the Goldstone bosons ( $w^\pm, z$  or equivalently the longitudinal components of the weak bosons  $W_L$  in high energy limit<sup>1</sup>), a scalar resonance  $H$ , a  $\rho$ -like vector resonance  $V$ , and other vector resonances such as  $A_1$  and  $\omega_H$  (analogous to  $a_1$  and  $\omega$  in low energy hadron physics). If the AW-type sum rules and the superconvergence relations are applied to  $W_L W_L$ ,  $W_L A_1$  and  $W_L V$  scatterings, one obtains the relations among the couplings and masses, which are fully expressed by two parameters: a mixing angle and one of the masses. This scenario has significant phenomenological consequences<sup>9</sup>. A comprehensive study including all of the states at future colliders is needed.

## 3. Signatures of SEWS at Future Colliders

In very high energy processes, there are many competing mechanisms to produce  $W$  bosons. Some of these are more sensitive than others to the EWSB sector involving the longitudinal components  $W_L$ <sup>10</sup>.

The vector-boson scattering process,  $W_L W_L \rightarrow W_L W_L$ , is clearly the most direct means to explore the EWSB sector and is especially important for the SEWS physics. The major advantage for studying the vector-boson fusion processes is that they involve all possible spin and isospin channels simultaneously, with scalar and vector resonances as well as non-resonant channels. For  $s \gg M_W^2$ , ignoring electroweak gauge couplings, the scattering of real longitudinal weak bosons is the same as the scattering of the corresponding Goldstone bosons, in accordance to the Equivalence Theorem<sup>1</sup>. In this case, the  $WW$  scattering amplitudes can be parametrized by a single amplitude function<sup>6</sup>. Furthermore, there is a generic property of complementarity<sup>11,6</sup>, namely: the  $W^+W^-$  and  $ZZ$  channels should be more sensitive to a scalar model;  $W^\pm Z$  and  $W^+W^-$  more sensitive to a vector model; and  $W^\pm W^\pm$  to a non-resonance model.

Another mechanism to produce vector boson pairs at future colliders is through light fermion anti-fermion annihilation. This is the case of light  $q\bar{q}$  annihilation in hadronic colliders (the Drell-Yan type mechanism<sup>12</sup>), as well as the case of  $e^+e^-$

annihilation in future  $e^+e^-$  colliders<sup>13</sup>. This production process is sensitive to new physics with a vector resonance intermediate state.

Finally, a mechanism for producing longitudinal vector boson pairs in hadronic colliders is gluon fusion. In this case the initial gluons turn into two vector bosons via an intermediate state that couples to both gluons and electroweak gauge bosons. This process may probe the SEWS physics in the heavy quark sector. In our phenomenological discussions below, we will mainly concentrate on the first two mechanisms, due to the consideration of signal identification and background suppression.

### 3.1. The Large Hadron Collider

The LHC should have good potential to probe the SEWS physics. The major difficulty is the large SM backgrounds. In order to detect the SEWS physics from the vector boson pair final state, we consider only the clean channels, the so-called “Gold plated” pure leptonic decay modes<sup>12</sup>. Table 1 presents the SM background and signal rates for the models described above. We see that

- the isoscalar model gives rise to substantial signal to background ratios in the  $ZZ \rightarrow 4\ell$  and  $ZZ \rightarrow 2\ell 2\nu$  channels. Especially encouraging is the signal rate for the  $2\ell 2\nu$  mode. The  $W^+W^-$  channel also exhibits some sensitivity to this model; the actual sensitivity is probably somewhat greater since the distribution in the mass variable  $M(\ell\ell)$  peaks broadly around half the mass of the scalar resonance<sup>14</sup>;
- the isovector models (Vec 1.0 and Vec 2.5) gives substantial signal in  $q\bar{q} \rightarrow V \rightarrow W^\pm Z$  channel for  $M_V \sim 1$  TeV, and yield a continuum event excess in the  $W^\pm W^\pm \rightarrow W^\pm W^\pm$  channel;
- the non-resonant model (LET-K) yields observable excesses in the  $W^\pm W^\pm$  channel.

The results clearly demonstrate that one should examine all vector boson pair channels and search for the deviation from the SM. From Table 1 for the  $W_L W_L$  signals and the predicted background rates, we can estimate the number of LHC years necessary to generate a signal at the 99% Confidence Level<sup>12</sup>. This is given in Table 2. We see that with a few years running at the LHC, one should be able to observe a significant enhancement in at least one gold-plated channel. Such an enhancement would be an important step towards revealing the physics of strongly interacting electroweak symmetry breaking.

More detailed simulations<sup>15</sup> agreed with our conclusions presented here. In particular, considering the semi-leptonic decay modes for a 1 TeV Higgs boson  $H \rightarrow WW \rightarrow \ell\nu jj$ , the signal observability can be substantially increased<sup>15,16</sup>.

Table 1: Event rates per LHC-year for  $W_L W_L$  fusion signals from the different models, together with backgrounds, assuming  $\sqrt{s} = 14$  TeV, an annual luminosity of  $100 \text{ fb}^{-1}$ , and  $m_t = 175$  GeV. Cuts are listed in Table I of Ref. 12. The  $W^\pm Z(DY)$  row refers to the DY process  $q\bar{q} \rightarrow V \rightarrow W^\pm Z$ , with  $0.85 < M_T(WZ) < 1.05$  TeV optimized for a 1 TeV vector state.

	Bkgd.	Scalar	Vec 1.0	Vec 2.5	LET-K
$ZZ(4\ell)$	0.7	4.6	1.4	1.3	1.4
$ZZ(2\ell 2\nu)$	1.8	17	4.7	4.4	4.5
$W^+W^-$	12	18	6.2	5.5	4.6
$W^\pm Z$	4.9	1.5	4.5	3.3	3.0
$W^\pm Z(DY)$	22		69		
$W^\pm W^\pm$	3.7	7.0	12	11	13

Table 2: Number of years (if  $< 10$ ) at LHC required for a 99% confidence level signal.

Channel	Model			
	Scalar	Vec 1.0	Vec 2.5	LET K
$ZZ(4\ell)$	2.5			
$ZZ(2\ell 2\nu)$	0.75	3.7	4.2	4.0
$W^+W^-$	1.5	8.5		
$W^\pm Z$		0.07		
$W^\pm W^\pm$	3.0	1.5	1.5	1.2

### 3.2. TeV $e^+e^-$ Linear Collider

Due to the cleaner experimental environment at the NLC, it may be desirable to study the hadronic decay modes to enlarge the signal sample for the  $WW$  final state. Our approach is based on  $W^+W^-$ ,  $ZZ \rightarrow (jj)(jj)$  four-jet signals, and therefore relies on good dijet mass resolution<sup>17</sup>.

Our main results are summarized in Table 3 for an  $e^+e^-$  (and  $e^-e^-$ ) collider at  $\sqrt{s} = 1.5$  TeV. They show that

- a 1-TeV scalar or vector state would be easily observable through the process  $W^+W^- \rightarrow ZZ$  and  $W^+W^-$ , respectively;
- a  $5.7\sigma$  signal for the LET amplitudes can be obtained via the  $W^+W^- \rightarrow ZZ$  channel alone;
- the  $W^+W^-/ZZ$  event ratio is a sensitive probe of SEWS dynamics. Indeed,

the differences between the various models are quite marked: a broad Higgs-like scalar will enhance both  $W^+W^-$  and  $ZZ$  channels with  $\sigma(W^+W^-) > \sigma(ZZ)$ ; a  $\rho$ -like vector resonance will manifest itself through  $W^+W^-$  but not  $ZZ$ ; the LET-K amplitude will enhance  $ZZ$  more than  $W^+W^-$ ;

- for an  $e^-e^-$  collider with the same energy and luminosity (see the last row in Table 3), the LET signal rate for the  $\nu\nu W^-W^-$  ( $I = 2$ ) channel is similar to the LET result of  $e^+e^- \rightarrow \bar{\nu}\nu ZZ$ , as anticipated, while the background rate is higher.

For a given luminosity, the signals are doubled for an  $e_L^-$  polarized beam (or quadrupled for two  $e_L^-$  beams), whereas the backgrounds increase by smaller factors. Hence polarization improves the significance of signals substantially<sup>17</sup>.

The direct  $s$ -channel process  $e^+e^- \rightarrow W^+W^-$  should be more advantageous in searching for effects from a vector  $V$  through  $\gamma, Z - V$  mixing, due to more efficient use of the CM energy, the known beam energy constraint, and better control of backgrounds. For instance, at a 1.5 TeV NLC with  $225 \text{ fb}^{-1}$  luminosity, a  $7\sigma$  effect may be obtained for a 4 TeV vector state<sup>13,18</sup>. Nevertheless, the  $WW$  fusion processes studied here involve more spin-isospin channels of  $WW$  scattering; they are unique for exploring scalar resonances and are complementary to the direct  $s$ -channel for the vector and non-resonant cases.

Table 3: Total numbers of  $W^+W^-$ ,  $ZZ \rightarrow 4\text{-jet}$  signal  $S$  and background  $B$  events calculated for a 1.5 TeV NLC with integrated luminosity  $200 \text{ fb}^{-1}$ . Events are summed over the mass range  $0.5 < M_{WW} < 1.5 \text{ TeV}$  except for the  $W^+W^-$  channel with a narrow vector resonance in which  $0.9 < M_{WW} < 1.1 \text{ TeV}$ . The statistical significance  $S/\sqrt{B}$  is also given. For comparison, results for  $e^-e^- \rightarrow \nu\nu W^-W^-$  are also presented, for the same energy and luminosity and the  $W^+W^-$  cuts. The hadronic branching fractions of  $WW$  decays and the  $W^\pm/Z$  identification/misidentification are included (see Ref. 17 for more details).

channels	Scalar $M_S = 1 \text{ TeV}$	Vector $M_V = 1 \text{ TeV}$	LET
$S(e^+e^- \rightarrow \bar{\nu}\nu W^+W^-)$	160	46	31
$B(\text{backgrounds})$	170	4.5	170
$S/\sqrt{B}$	12	22	2.4
$S(e^+e^- \rightarrow \bar{\nu}\nu ZZ)$	130	36	45
$B(\text{backgrounds})$	63	63	63
$S/\sqrt{B}$	17	4.5	5.7
$S(e^-e^- \rightarrow \nu\nu W^-W^-)$	35	36	42
$B(\text{backgrounds})$	230	230	230
$S/\sqrt{B}$	2.3	2.4	2.8



### 3.3. A 4 TeV muon Collider

Achieving  $WW$  subprocess energies above 1 – 2 TeV is critical for studies of the SEWS physics, and is only possible with high event rates at lepton-antilepton ( $e^+e^-$  or  $\mu^+\mu^-$  colliders) or quark-antiquark (hadron collider) subprocess energies of order 3 – 4 TeV.

Table 4: Total numbers of  $W^+W^-$ ,  $ZZ$  and  $W^+W^+ \rightarrow 4\text{-jet}$  signal ( $S$ ) and background ( $B$ ) events calculated for a 4 TeV  $\mu^+\mu^-$  collider with integrated luminosity 200 fb $^{-1}$  (1000 fb $^{-1}$  in the parentheses), for acceptance cuts as detailed in Ref. 19. The statistical significance  $S/\sqrt{B}$  is given for the signal from each model. The hadronic branching fractions of the decays and the  $W^\pm/Z$  identification/misidentification are included.

channels	Scalar $m_H = 1$ TeV $\Gamma_H = 0.5$ TeV	Vector $M_V = 2$ TeV $\Gamma_V = 0.2$ TeV	LET-K ( $m_H = \infty$ ) Unitarized
$\mu^+\mu^- \rightarrow \bar{\nu}\nu W^+W^-$			
$S(\text{signal})$	2400 (12000)	180 (890)	370 (1800)
$B(\text{backgrounds})$	1200 (6100)	25 (120)	1200 (6100)
$S/\sqrt{B}$	68 (152)	36 (81)	11 (24)
$\mu^+\mu^- \rightarrow \bar{\nu}\nu ZZ$			
$S(\text{signal})$	1030 (5100)	360 (1800)	400 (2000)
$B(\text{backgrounds})$	160 (800)	160 (800)	160 (800)
$S/\sqrt{B}$	81 (180)	28 (64)	32 (71)
$\mu^+\mu^+ \rightarrow \bar{\nu}\nu W^+W^+$			
$S(\text{signal})$	240 (1200)	530 (2500)	640 (3200)
$B(\text{backgrounds})$	1300 (6400)	1300 (6400)	1300 (6400)
$S/\sqrt{B}$	7 (15)	15 (33)	18 (40)

Consequently, a muon collider facility with center of mass energy  $\sqrt{s} \sim 3 - 4$  TeV and luminosity  $L = 200 - 1000$  fb $^{-1}$  allowing both  $\mu^+\mu^-$  and  $\mu^+\mu^+$  (or  $\mu^-\mu^-$ ) collisions would be a remarkably powerful machine for probing the SEWS physics. Table 4 presents the signal and background rates at a 4-TeV muon collider<sup>19</sup>. We see that

- the statistical significance of the SEWS signal is high for all channels, regardless of model. Even the  $W^+W^-$  signal for LET-K and  $W^+W^+$  signal for  $m_H = 1$  TeV are clearly visible with only  $L = 200$  fb $^{-1}$ , becoming thoroughly robust for  $L = 1000$  fb $^{-1}$ ;
- models of distinctly different types are easily distinguished from one another, as previously discussed in the NLC study and as more clearly demonstrated in

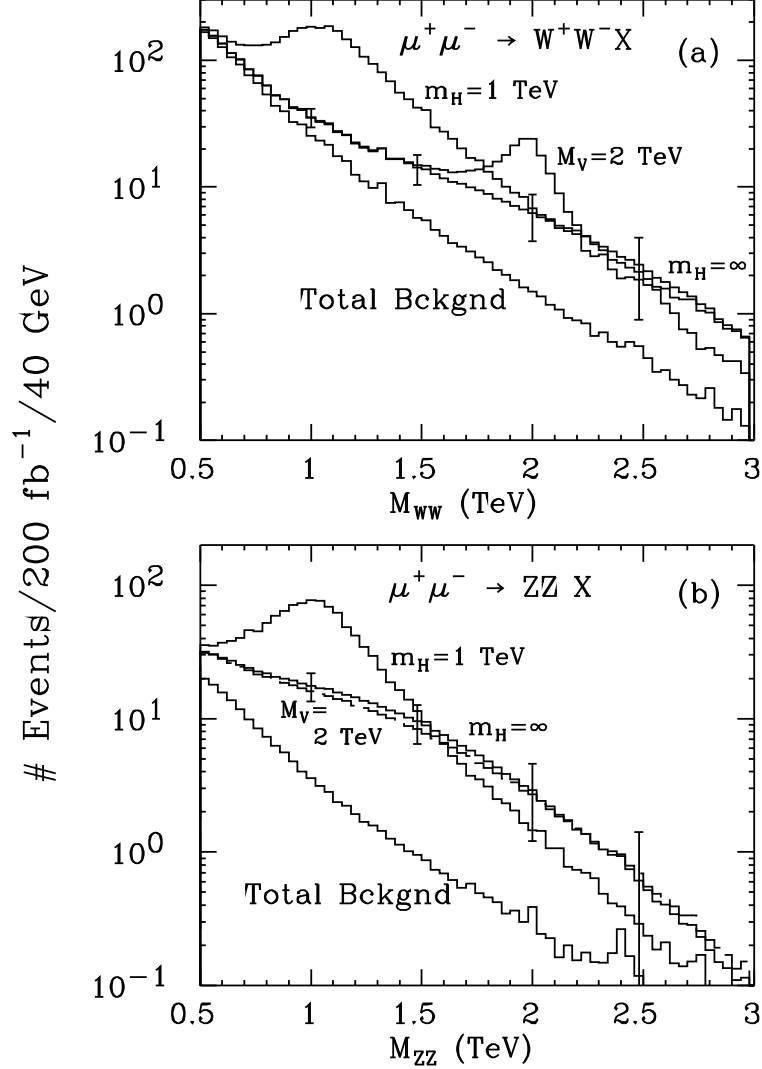


Fig. 1. Number of events at a 4-TeV muon collider with  $L = 200 \text{ fb}^{-1}$  for SEWS models (including the combined backgrounds) and for the combined backgrounds alone in the (a)  $W^+W^-$  and (b)  $ZZ$  final states after imposing all acceptance cuts as detailed in Ref. 19. Sample signals shown are: (i) the SM Higgs with  $m_H = 1 \text{ TeV}$ ; (ii) LET-K model (denoted by  $m_H = \infty$ ); and (iii) the Vector model with  $M_V = 2 \text{ TeV}$  and  $\Gamma_V = 0.2 \text{ TeV}$ . Sample statistical uncertainties for the illustrated 40 GeV bins are shown in the case of the LET-K model.

Fig. 1(a)–(b).

- event rates for even the weakest of the model signals studied are such that the  $M(WW)$  distributions could be quantitatively delineated, thereby providing a direct measurement of the underlying strong  $WW$  interaction amplitude as a function of the subprocess energy and strong differentiation among various possible models of the strongly interacting electroweak sector;
- statistics are even sufficient that a model-independent projection analysis can be applied to isolate the polarization  $TT$ ,  $TL$  and  $LL$  components of the cross section<sup>19</sup>. This would further delineate the correct theory underlying the strong electroweak interactions based on the polarization studies for the final state  $WW$ .

#### 4. Summary

A strongly interacting electroweak sector remains a logical possibility responsible for the electroweak symmetry breaking. A phenomenological approach by adopting a (relatively) model-independent parameterization for such a sector is taken to study the sensitivity to the SEWS physics at future colliders. We find that

1. at the LHC with  $\sqrt{s} = 14$  TeV, an observable excess of events in the pure leptonic  $W$  decay modes can be seen for all of the strongly interacting models that we consider, after several years of running with an annual luminosity of  $100 \text{ fb}^{-1}$ . The major problem for observing SEWS effects is the large SM background and rather low pure leptonic final state rates for the signals;
2. due to the clean experimental environment at an  $e^+e^-$  collider, the hadronic  $W$ -decay modes may be used for searching for SEWS  $WW$  events. This leads to a large signal sample if the SEWS physics emerges near about 1 TeV region. On the other hand, the available CM energy of about 1.5 TeV may limit the SEWS physics reach, except for a vector dominant model. The  $e^-$  beam polarization could help to enhance the signal observability. The option for an  $e\gamma$  collider may be useful to uniquely produce other states through  $\gamma W \rightarrow A_1$  and  $\gamma Z \rightarrow \omega_H$ ;
3. to fully explore  $WW$  scattering physics at 1–2 TeV, a muon collider facility with center of mass energy  $\sqrt{s} \sim 3\text{--}4$  TeV and luminosity  $L = 200\text{--}1000 \text{ fb}^{-1}$  would be a remarkably powerful machine. It not only yields sufficiently large event rates for SEWS signals, but also allows detailed study for the signal structure to uncover the possible underlying dynamics.

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